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# TRANSIENT BEAM DYNAMICS IN THE LBL 2 MV INJECTOR*

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*ABSTRACT*

A driver-scale injector for the Heavy Ion Fusion Accelerator project has been built at LBL. This machine has exceeded the design goals of high voltage (> 2 MV), high current (> 0.8 A of $K^+$) and low normalized emittance (< 1 $\pi$ mm-mr). The injector consists of a 750 keV gun pre-injector followed by an electrostatic quadrupole accelerator (ESQ) which provides strong (alternating gradient) focusing for the space-charge dominated beam, and simultaneously accelerates the ions to 2 MeV. A matching section is being built to match the beam to the electrostatic accelerator ELISE. The gun pre-injector, designed to hold up to 1 MV with minimal breakdown risks, consists of a hot alumino-silicate source with a large curved emitting surface surrounded by a thick "extraction electrode." During beam turn-on the voltage at the source is biased from a negative potential, enough to reverse the electric field on the emitting surface and avoid emission, to a positive potential to start extracting the beam; it stays constant for about 1 μs, and is reversed to turn-off the emission. Since the Marx voltage applied on the accelerating quadrupoles and the main pre-injector gap is a long, constant pulse (several μs), the transient behavior is dominated by the extraction pulser voltage time profile. The transient longitudinal dynamics of the beam in the injector was simulated by running the Particle in Cell codes GYMNOS and WARP3d in a time dependent mode. The generalization and its implementation in WARP3d of a method proposed by Lampel and Tiefenback to eliminate transient oscillations in a one-dimensional planar diode will be presented.

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## I. INTRODUCTION

The design of the 750 keV gun pre-injector, using the gun code EGUN [1], is based on the steady-state space-charge dominated (Child-Langmuir) flow. The relationship between the time-dependent voltage on the "extracting electrode" and the current and energy at the end of the 2 MeV Injector was calculated by the PIC codes GYMNOS[2] and WARP3d[3]. Figure 1 shows current and energy transient oscillations, which decay away within a few multiples of the particle transit time across the gun, for the case of a sudden turn-on of the extracting voltage. The elimination of these oscillations is very important for space-charge dominated beams since such oscillations will lead to envelope variations along the beam which will reduce the dynamic aperture of the accelerator.

This paper discusses the generalization, to any complex geometry, of a method proposed by Lampel and Tiefenback [4] to eliminate transient oscillations in a one-dimensional planar diode.

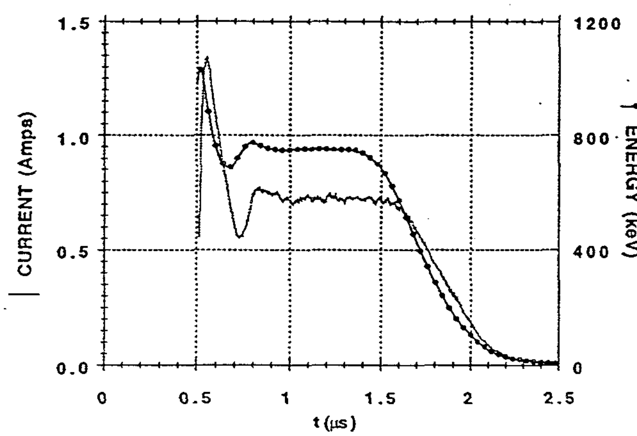


Figure 1: Current and energy transient oscillations for the case of a sudden turn-on of the extracting voltage.

## II. CURRENT TRANSIENT ELIMINATION IN A 1-D PLANAR DIODE

In a one-dimensional planar diode it is possible to find an analytic solution for the extracting voltage waveform that will eliminate the current and energy transient oscillations.

Figure 2 shows a schematic diagram of a planar diode. Let $\phi(x)$ be the potential corresponding to the steady-state space-charge dominated flow:

$$\phi(x) = -V\ (x/L)^{4/3}.$$

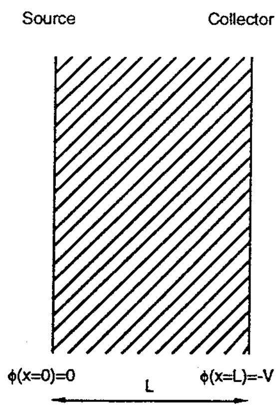


Figure 2: Schematic diagram of a planar diode.

**a) Correction of beam head oscillations (Lampel and Tiefenback, 1983).**

To calculate the required V(t) we use the following procedure starting from the steady-state solution:

• Divide the diode into two regions on either side of the plane at $x=\xi$.

• Eliminate the charge for $x>\xi$. See Figure 3.

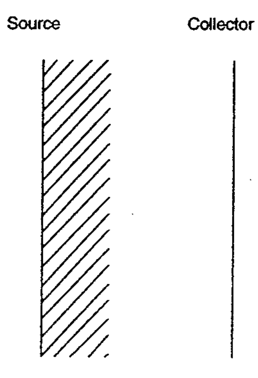


Figure 3: Beam head uniform current flow.

• Keep field solution for $x<\xi$ unchanged by requiring the field at $x=\xi$ to be the same as in the steady-state space-charge dominated flow.

• Change potential at the collector to satisfy Laplace's equation for $x>\xi$, and continuity of potential and field at $x=\xi$. The solution in terms of the parameter $\xi$ is:

$$\psi_c(\xi) = -V\ [4/3\ (\xi/L)^{1/3} - 1/3\ (\xi/L)^{4/3}\ ]$$

• Express the parameter $\xi$ in terms of the time at which the leading particles in the beam are at $\xi$. From energy conservation we get:

$$1/2\ m\ (d\xi/dt)^2 = qV\ (\xi/L)^{4/3}.$$

By integrating the preceding equation we obtain:

$$\xi/L = (t/\tau)^3,$$

where the transit time factor is defined as:

$$\tau = 3\ \sqrt{(mL^2/(2qV))}.$$

Since $V(t)=\psi_c(\xi)$, the beam-head oscillations will be corrected by applying the following voltage waveform at the collector:

$$V(t) = -V\ [4/3\ (t/\tau) - 1/3\ (t/\tau)^4\ ] \quad \text{for} \quad t<\tau,$$
$$V(t) = -V \quad \text{for} \quad t>\tau.$$

**b) Correction of beam tail oscillations.**

The procedure can be extended to eliminate beam tail oscillations by dividing the diode into two regions on either side of the plane at $x=\xi$, eliminating the charge for $x<\xi$ (see Figure 4), keeping field solution for $x>\xi$ unchanged by requiring the field at $x=\xi$ to be the same as in the steady-state space-charge dominated flow, and changing the potential at the collector to satisfy Laplace's equation for $x<\xi$, and continuity of potential and field at $x=\xi$. The solution in terms of the parameter $\xi$ is:

$$\psi_c(\xi)\ = -V\ [1 + 1/3\ (\xi/L)^{4/3}\ ]$$

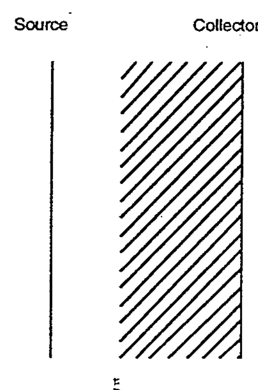


Figure 4: Beam tail uniform current flow.

Taking the time origin as the time when the emission stops, the beam tail oscillations will be corrected by applying the following voltage waveform at the collector:

$$V(t) = -V\ [1 + 1/3\ (t/\tau)^4\ ] \quad \text{for} \quad t>\tau.$$

## III. CURRENT TRANSIENT ELIMINATION BETWEEN CONCENTRIC SPHERES

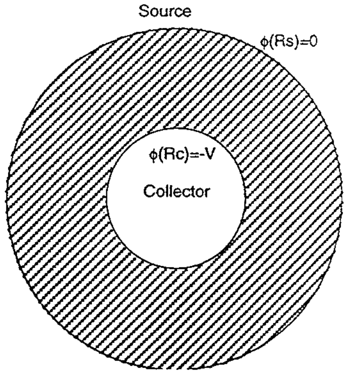


Figure 5: Schematic diagram of a concentric-spheres diode.

For Child-Langmuir flow between concentric spheres (or between infinite coaxial cylinders) the procedure described above provides a set of ordinary differential equations whereby a solution for the extracting voltage wave-form will be obtained that will eliminate the current and energy transient oscillations.

Figure 5 shows a schematic diagram of a diode formed by two concentric spheres. Let $\phi(r)$ be the potential corresponding to the steady-state space-charge dominated flow:

$$1/r^2 \, d/dr \, (r^2 \, d\phi/dr) = -\rho/\varepsilon_0.$$

Since

$$1/2 \, m \, v^2 = -q\phi \quad \text{and} \quad \rho = I/(4\pi r^2 v),$$

then

$$d/dr \, (r^2 \, d\phi/dr) = -I/(4\pi\varepsilon_0) \sqrt{(-m/(2q\phi))}$$

where v and I are the beam velocity and current, respectively.

To correct for beam-head transients we will follow the same procedure described above, starting from the steady-state Child-Langmuir flow solution:

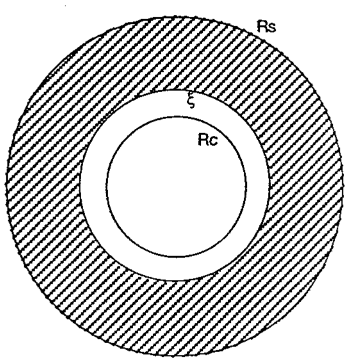


Figure 6: Beam head uniform current flow.

- Divide the diode into two regions on either side of the sphere at $r=\xi$.
- Eliminate the charge for $r<\xi$. See Figure 6.
- Keep field solution for $r>\xi$ unchanged by requiring the field at $r=\xi$ to be the same as in the steady-state space-charge dominated flow.
- Change potential at the collector to satisfy Laplace's equation for $r<\xi$, and continuity of potential and field at $r=\xi$. The solution in terms of the parameter $\xi$ is:

$$\psi_c(\xi) = \xi^2 \, (1/\xi - 1/R_c) \, \phi'(\xi) + \phi(\xi) \, .$$

- Express the parameter $\xi$ in terms of the time at which the leading particles in the beam are at $\xi$. From energy conservation we get (inward flow):

$$1/2 \, m \, (d\xi/dt)^2 = -q\phi.$$

Since we do not have a closed form solution for $\phi(r)$, then V(t) will be obtained by integrating numerically Poisson's and the velocity equations to obtain $\phi(\xi)$ and $t(\xi)$. The initial conditions are:

$$\phi(R_s) = 0 \, ,$$
$$\phi'(R_s) = 0 \, ,$$
$$\tau(R_s) = 0 \, .$$

Since $V(t)=\psi_c(\xi)$, we obtain the required voltage wave-form by substituting these solutions into the expression for $\psi_c(\xi)$.

A similar analysis, following a different approach, has been reported by Kadish et al. [5]

Particle codes written to study the beam dynamics of one-dimesional diodes have been used to check the validity of the procedure. [6,7,8]

## IV. CURRENT TRANSIENT ELIMINATION IN GENERAL GEOMETRIES

The essential feature of the described procedure is to force the field solution in the region occupied by the beam, at any given time, to be the same as the steady-state solution in the same region. This can be done in one-dimensional structures by prescribing an extracting voltage wave-form V(t) since a condition at a single point (the collector) is enough to fulfill the requirement.

For a two- and three-dimensional gun the procedure requires the prescription of extracting voltage wave-forms along a curve or on a surface, respectively. Since this requirement is not attainable we can compensate only partially the transient oscillations. For an axisymmetric structure, for example, one could use as an effective potential the average energy of the particles at a given cross section, and follow the same procedure as the one described for one-dimensional structures.

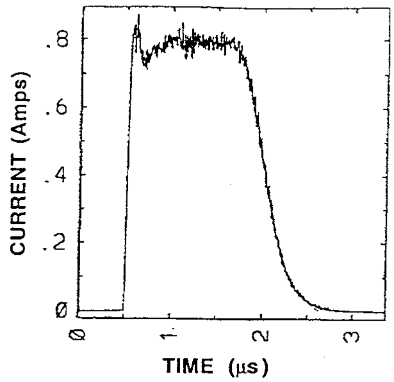


Figure 7: Current profile for the 2 MeV Injector using the numerically-calculated voltage wave-form.

We have implemented the general procedure to eliminate transient oscillations in the three-dimensional PIC code WARP3d. Figure 7 shows the current at the end of the cylindrically symmetric 2 MeV Injector using the numerically calculated voltage wave-form V(t) applied on the extracting electrode. The resulting current profile shows a decrease in the beam-head transient oscillation. Since the 2 MeV HIF Injector Gun is poorly represented by either a planar diode or a two-concentric-sphere diode, attempts to use the voltage wave-forms V(t) calculated for such geometries resulted in a rather small decrease of the transient oscillation. Figure 8 compares the voltage vave-forms numerically-calculated with the wave-forms obtained for the planar and spherical diodes.

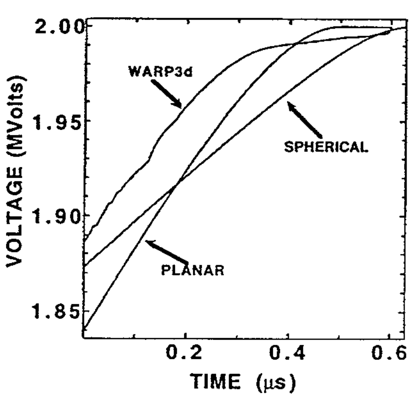


Figure 8: Voltage wave-form as calculated and used in WARP3d, and the corresponding ideal wave-forms for the planar- and spherical-equivalent diodes.

## V. CONCLUSION

A generalization, to any complex geometry, of a method proposed by Lampel and Tiefenback to eliminate transient oscillations in a one-dimensional planar diode has been shown to give good results when implemented numerically in the three-dimensional PIC code WARP3d.

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